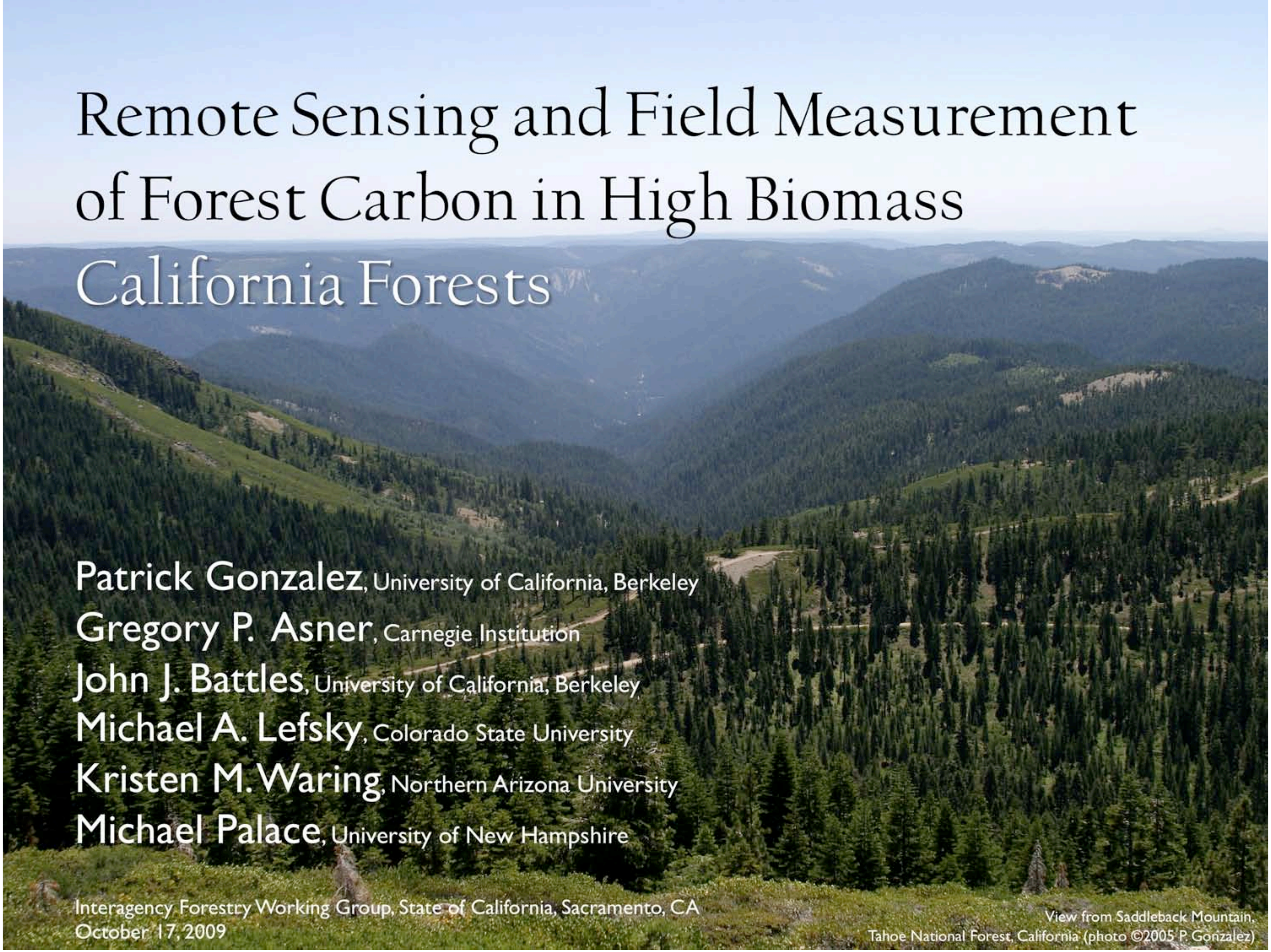


Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Patrick Gonzalez, University of California, Berkeley
Gregory P. Asner, Carnegie Institution
John J. Battles, University of California, Berkeley
Michael A. Lefsky, Colorado State University
Kristen M. Waring, Northern Arizona University
Michael Palace, University of New Hampshire

Interagency Forestry Working Group, State of California, Sacramento, CA
October 17, 2009

View from Saddleback Mountain,
Tahoe National Forest, California (photo ©2005 P. Gonzalez)

Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Funding

U.S. Department of Energy,
National Energy Technology Laboratory
Nature Conservancy
California Agricultural Experiment Station

Research Partners

Carnegie Institution
Colorado State University
U.S. Department of Agriculture,
Forest Service
University of California, Berkeley

Acknowledgements

U.S. Department of Agriculture, Forest Service
Steve Eubanks (Forest Supervisor)
Alan Doerr
Terri Walsh
Other Staff of the Tahoe National Forest
UC Berkeley Forest Inventory Crew
Garrett Meigs (crew leader)
Tim Faye
Mike O'Brien
Anne Pinckard
Emily Solie
California Department of Parks and Recreation
Renee Pasquinelli
Conservation Fund
Jenny Griffin
Nature Conservancy
Louis Blumberg
Bill Stanley

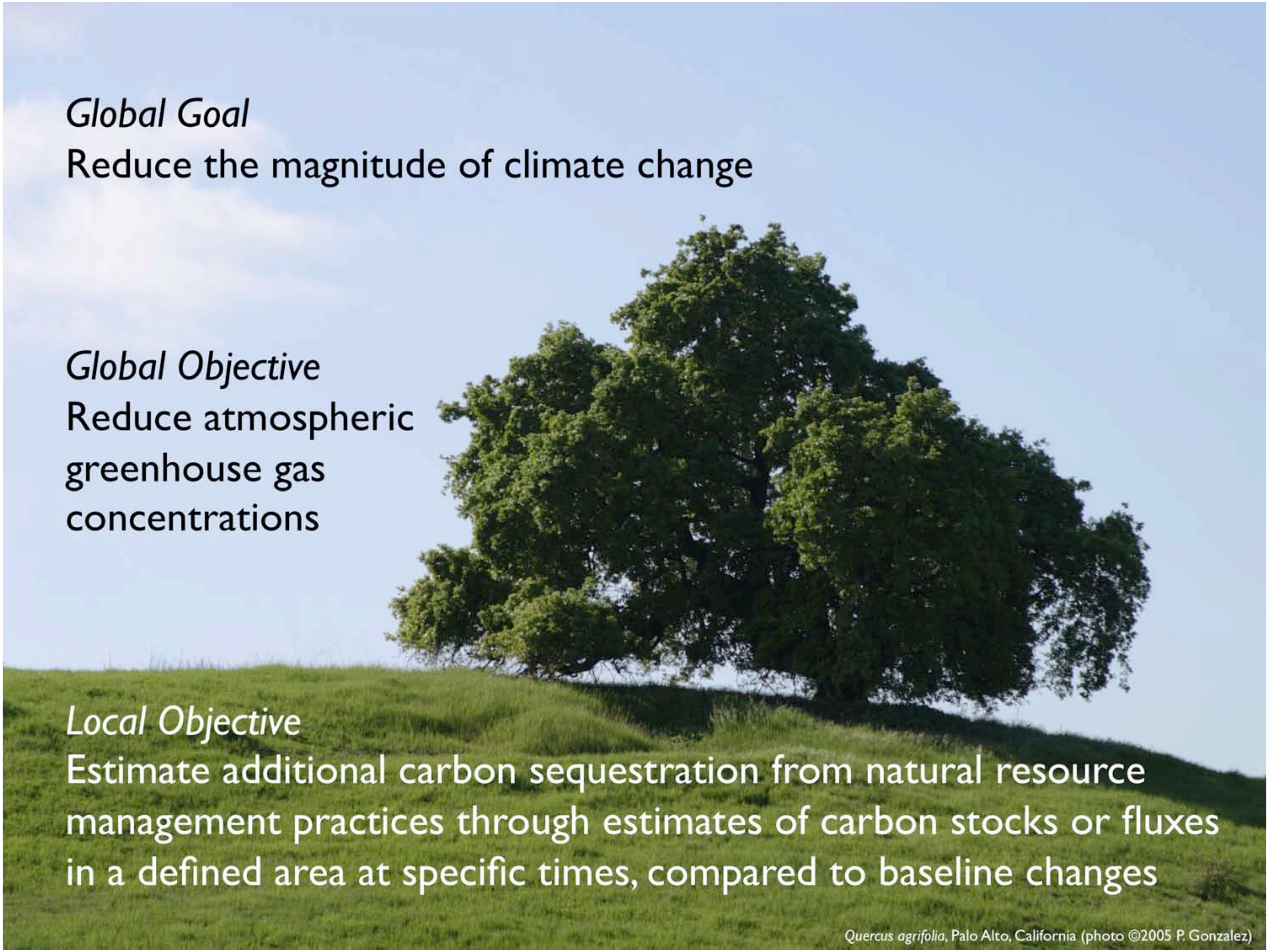
Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Presentation Outline

1. Introduction (forest carbon monitoring)
2. Methods (research in Sierra Nevada and Coast Redwood forests)
3. Results (research in Sierra Nevada and Coast Redwood forests)
4. Conclusions

Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Introduction



Quercus agrifolia, Palo Alto, California (photo ©2005 P. Gonzalez)

Local Objective

Estimate additional carbon sequestration from natural resource management through estimates of carbon stocks or fluxes in a defined area at specific times, compared to baseline changes

$$\Delta C_{\text{additional}} = \frac{C_2 - C_1}{t_2 - t_1} - \Delta C_{\text{baseline}}$$

$\Delta C_{additional}$ = carbon emission or removal due to an additional natural resource management activity

C_t = carbon stock of an area at a specific time

t = time

$\Delta C_{baseline}$ = baseline change that would occur in absence of the natural resource management activity

IPCC Greenhouse Gas Categories and Methods

Land Use	Greenhouse Gases	Carbon Pools	Aboveground Biomass
Forest land	CO_2	Aboveground biomass	Mature trees
Cropland	CH_4	Deadwood	Understory trees
Grassland	N_2O	Litter	Shrubs
Wetland	HFCs	Harvested wood products	Grasses
Settlements	PFCs	Belowground biomass	
Other land	SF_6	Soil organic carbon	

Carbon Methods	Uncertainty Methods
Gain-loss (fluxes)	Simple error propagation
Stock difference	Monte Carlo

Reference

Aalde, H., P. Gonzalez, M. Gytarsky, T. Krug, W. Kurz, S. Ogle, J. Raison, D. Schoene, and N.H. Ravindranath. 2006. Forest Land. In Intergovernmental Panel on Climate Change (IPCC). National Greenhouse Gas Inventory Guidelines. Institute for Global Environmental Strategies, Hayama, Japan.

IPCC Greenhouse Gas Categories and Methods

Land Use	Greenhouse Gases	Carbon Pools	Aboveground Biomass
Forest land	CO_2	Aboveground biomass	Mature trees
Cropland	CH_4	Deadwood	Understory trees
Grassland	N_2O	Litter	Shrubs
Wetland	HFCs	Harvested wood products	Grasses
Settlements	PFCs	Belowground biomass	
Other land	SF_6	Soil organic carbon	

Carbon Methods	Uncertainty Methods
Gain-loss (fluxes)	Simple error propagation
Stock difference	Monte Carlo

Research

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review. Forest Carbon Densities and Uncertainties from Lidar, QuickBird, and Field Measurements in California.

Some Remote Sensing Options for Forest Carbon

North Yuba Forest Carbon Plot B4, California

Terra Satellite
MODIS sensor
250 m spatial resolution

36 spectral bands
Data 2000-present, free
Carbon by land class
Plot Image August 1, 2005

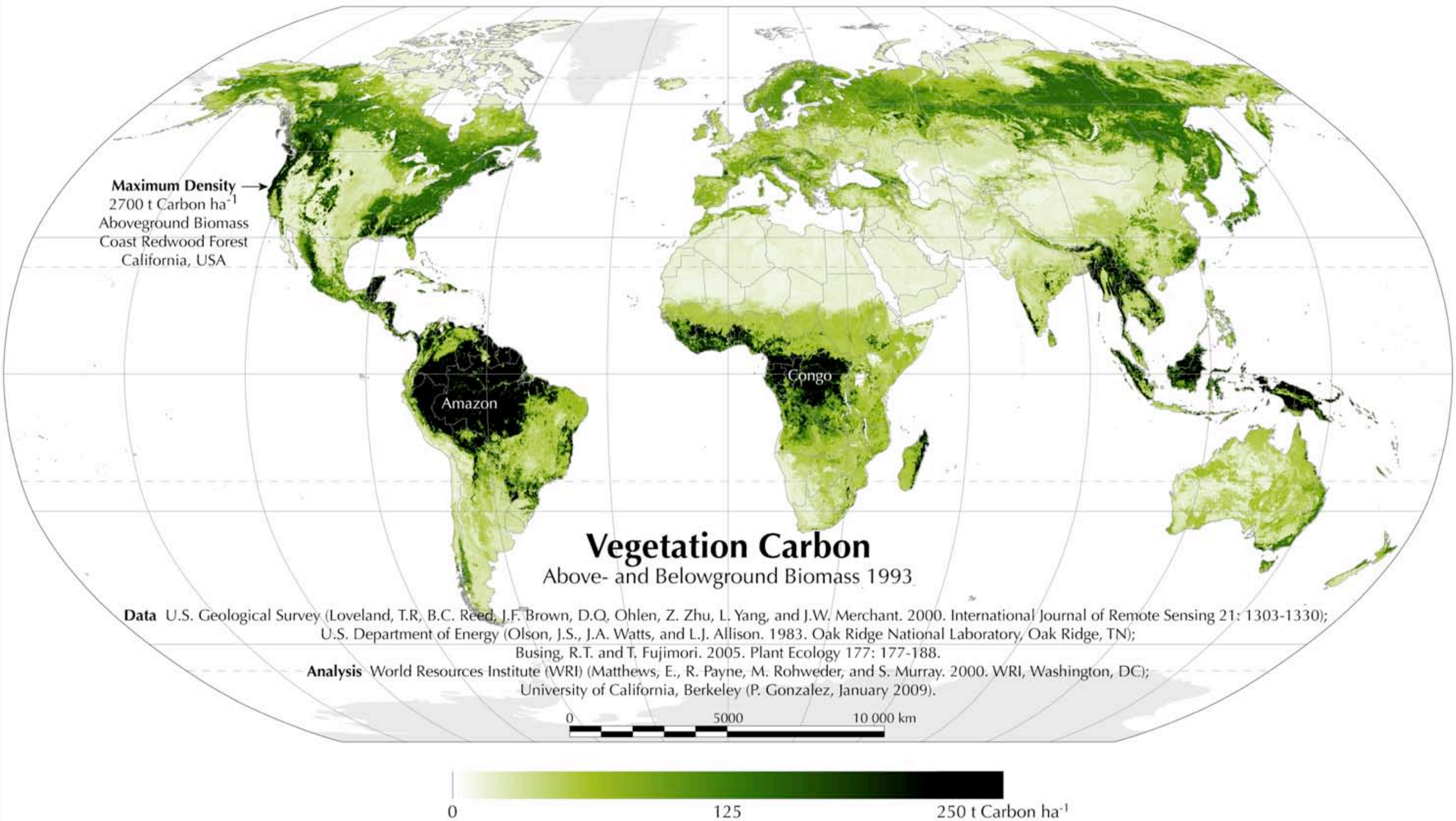
Landsat Satellite
ETM+ sensor
30 m spatial resolution

9 spectral bands
Data 1972-present, free
Carbon by land class
Plot Image July 18, 2000

QuickBird
Satellite
0.6 m spatial resolution

5 spectral bands
Data 2001-present, for sale
Carbon by tree or stand
Plot Image August 2, 2009

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.



Maximum Density
2700 t Carbon ha-1
Aboveground Biomass
Coast Redwood Forest
California, USA
Amazon
Congo
Vegetation Carbon
Above- and Belowground Biomass 1993
Data U.S. Geological Survey (Loveland, T.R, B.C. Reed, J.F. Brown, D.O. Ohlen, Z. Zhu, L. Yang, and J.W. Merchant. 2000. International Journal of Remote Sensing 21: 1303-1330);
U.S. Department of Energy (Olson, J.S., J.A. Watts, and L.J. Allison. 1983. Oak Ridge National Laboratory, Oak Ridge, TN);
Busing, R.T. and T. Fujimori. 2005. Plant Ecology 177: 177-188.
Analysis World Resources Institute (WRI) (Matthews, E., R. Payne, M. Rohweder, and S. Murray. 2000. WRI, Washington, DC);
University of California, Berkeley (P. Gonzalez, January 2009).
0
5000
10 000 km
0
125
250 t Carbon ha-1

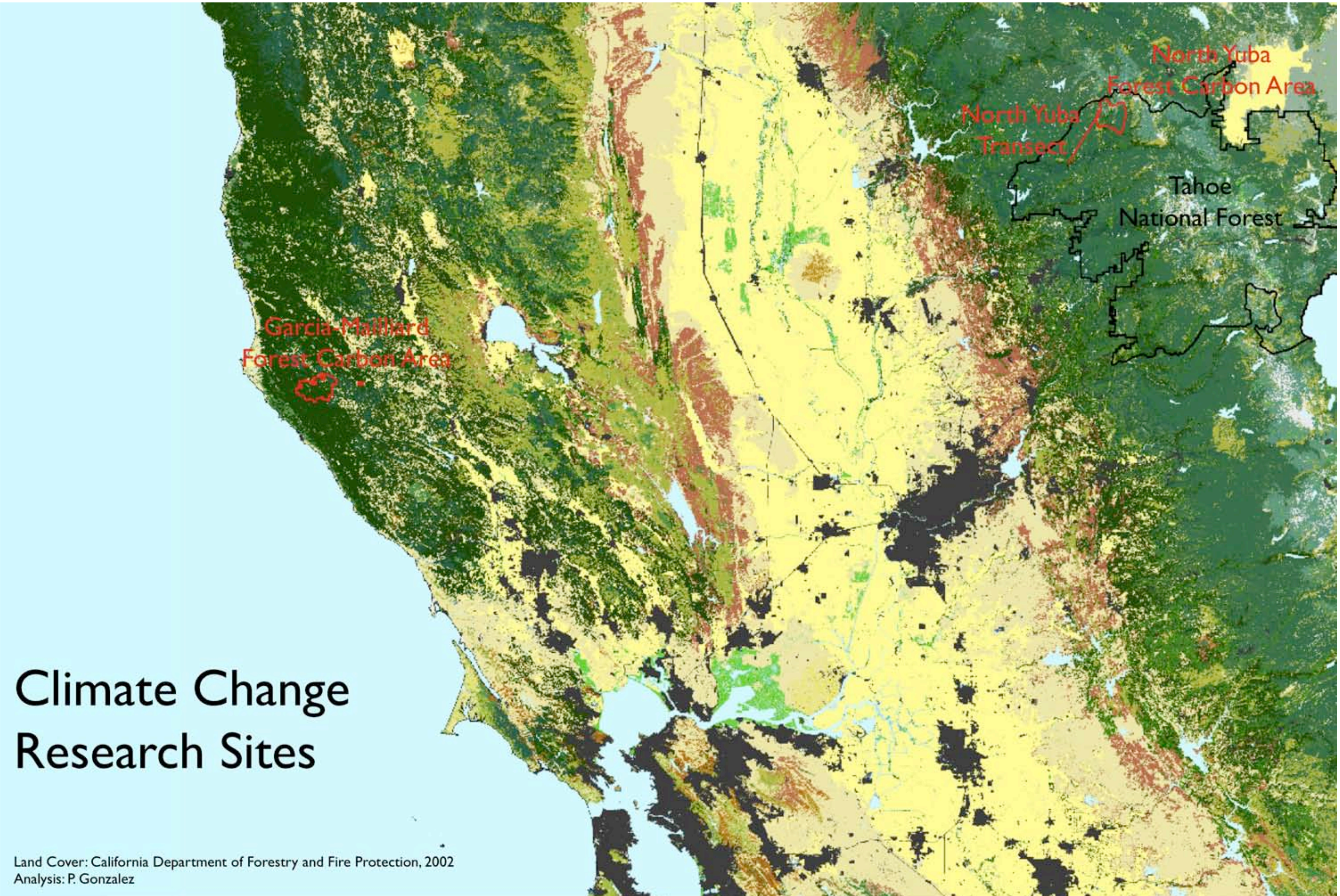
Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Methods

Forest Carbon Densities and Uncertainties from Lidar, QuickBird, and Field Measurements in California

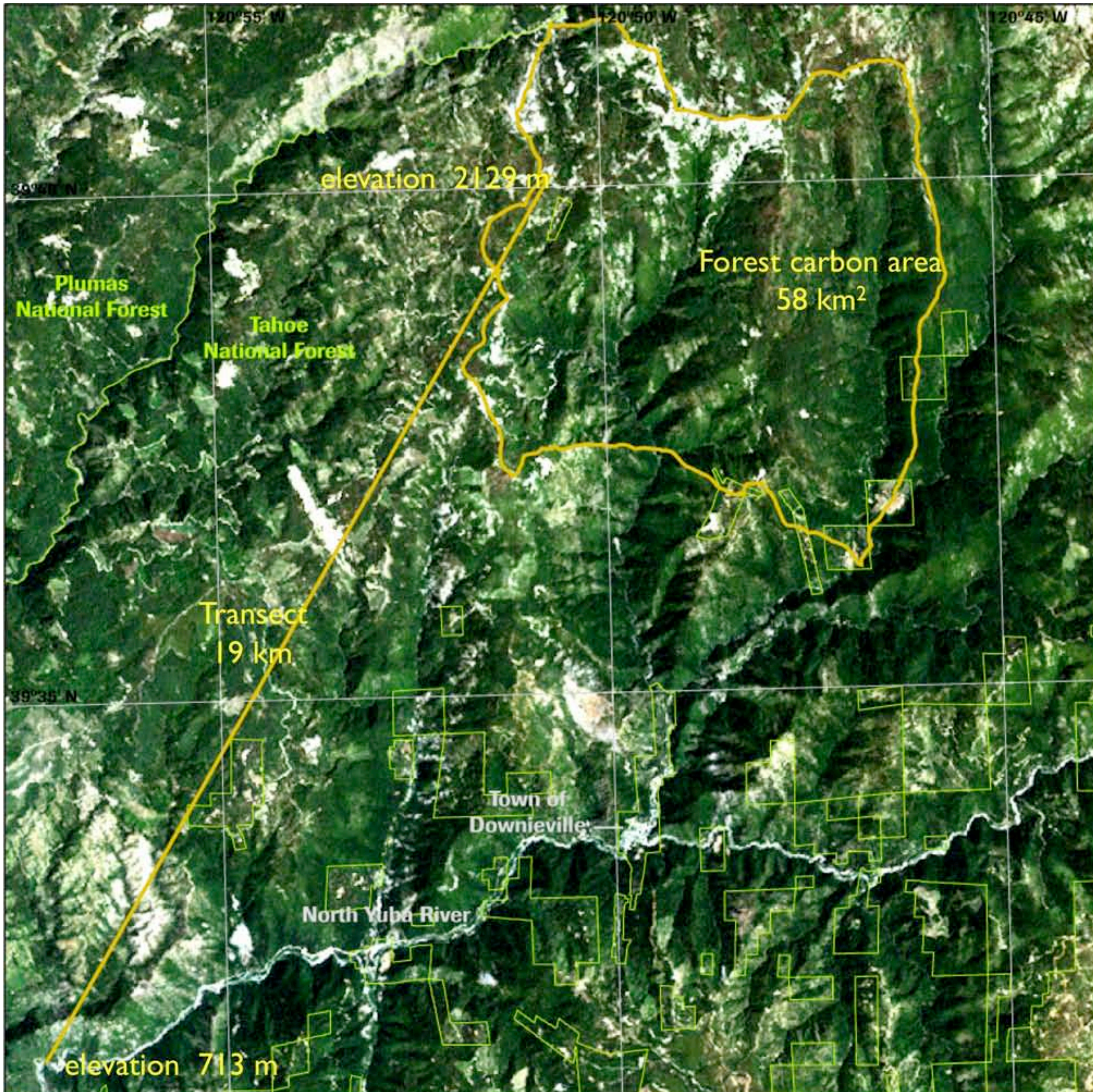
Research Objectives

1. Assess the accuracy of Lidar and QuickBird remote sensing to quantify forest carbon
2. Quantify forest carbon in two high biomass forests
3. Develop a method to use in reduced deforestation and degradation (REDD) projects



Climate Change Research Sites

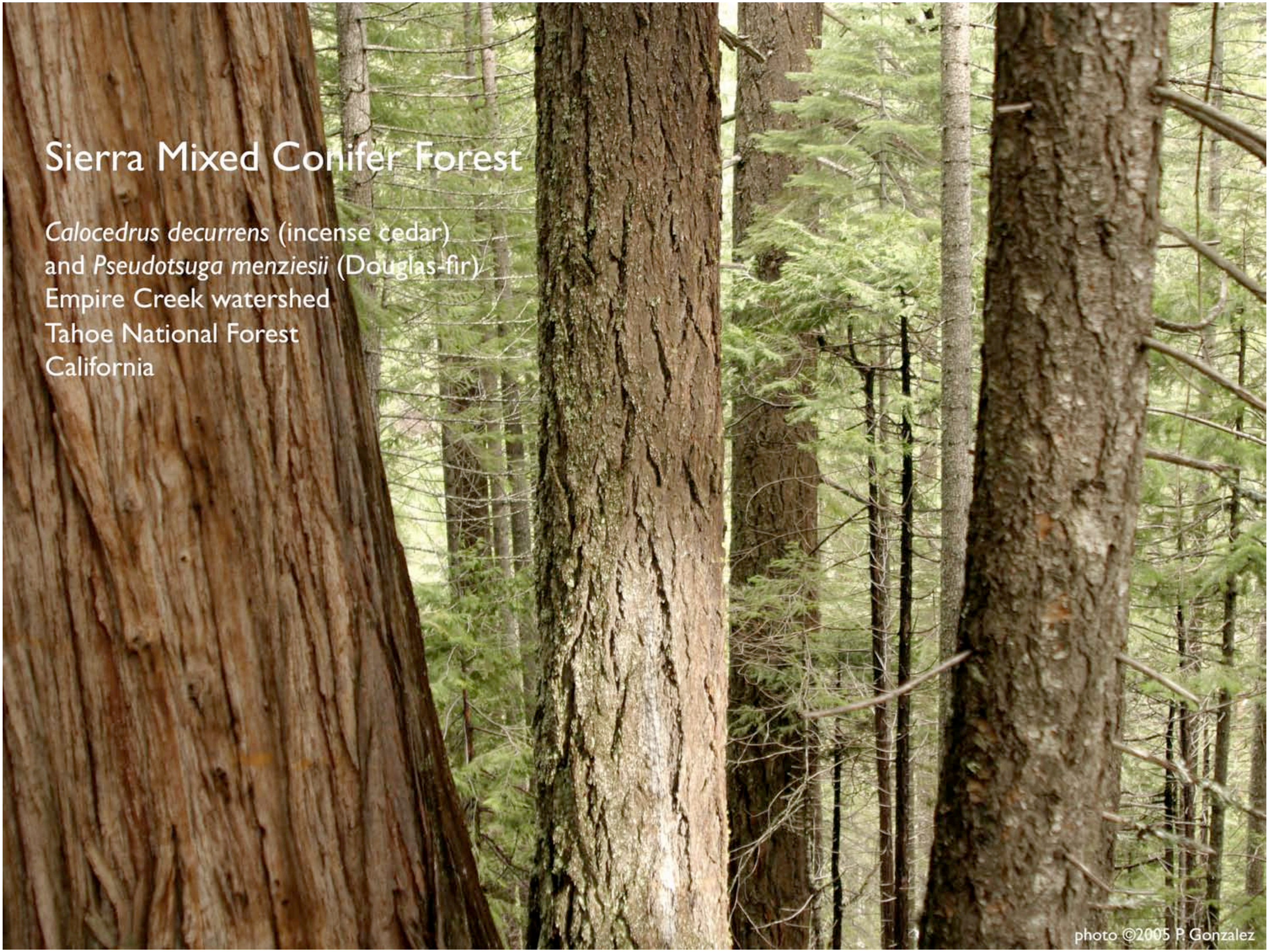
Land Cover: California Department of Forestry and Fire Protection, 2002
Analysis: P. Gonzalez



Tahoe National Forest Climate Change Research Areas

image USGS Landsat, July 18, 2000
data USDA FS
analysis P. Gonzalez

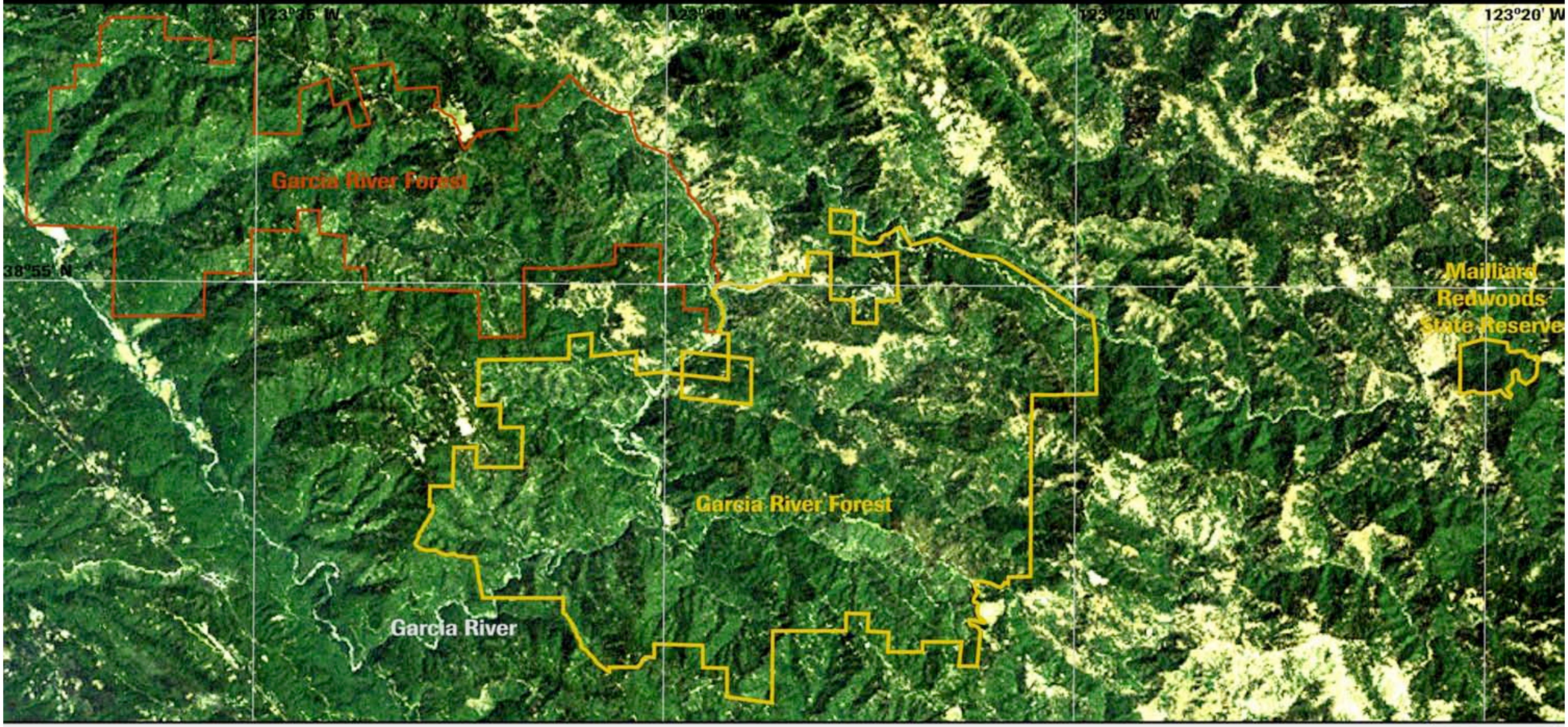

Montane Hardwood
Quercus kelloggii (California black oak)
and Quercus chrysolepis (canyon live oak)
North Yuba River area
Tahoe National Forest
California
photo ©2007 P. Gonzalez


Sierra Mixed Conifer Forest
Calocedrus decurrens (incense cedar)
and *Pseudotsuga menziesii* (Douglas-fir)
Empire Creek watershed
Tahoe National Forest
California
photo ©2005 P. Gonzalez

Red Fir Forest

Abies magnifica (red fir),
below Democrat Peak
Tahoe National Forest
California

Garcia River Forest
Mailliard Redwoods State Reserve, California



Forest Carbon Research

The Nature Conservancy
The Conservation Fund
California Department of Parks and Recreation
U.S. Department of Energy
Carnegie Institution of Washington
Colorado State University
Stanford University
University of California, Berkeley

forest carbon area
Garcia River Forest, west unit

0 2.5 5 km

scale 1:125 000
projection UTM 10 N, horizontal datum NAD83

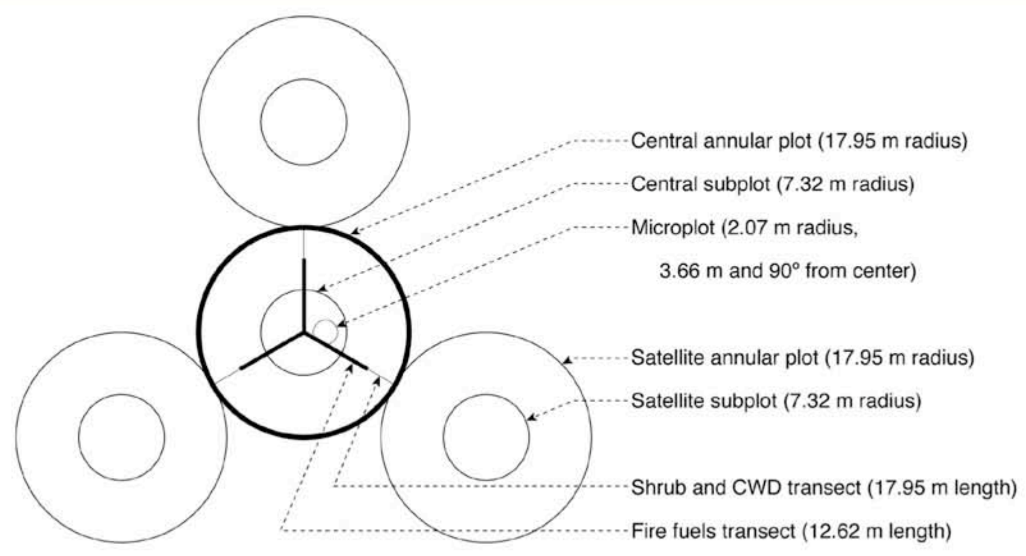
remote sensing: U.S. Geological Survey, Landsat, August 17, 2000
cartography: The Nature Conservancy, P. Gonzalez, May 2005


Secondary Growth Coast Redwood
Sequoia sempervirens (coast redwood)
and *Lithocarpus densiflorus* (tanoak)
Garcia River forest
California
photo ©2005 P. Gonzalez


Old-Growth Coast Redwood
Sequoia sempervirens (coast redwood)
and *Pseudotsuga menziesii* (Douglas-fir)
Mailliard Redwoods State Natural Reserve
California
photo ©2006 P. Gonzalez

Forest Carbon Monitoring Plots

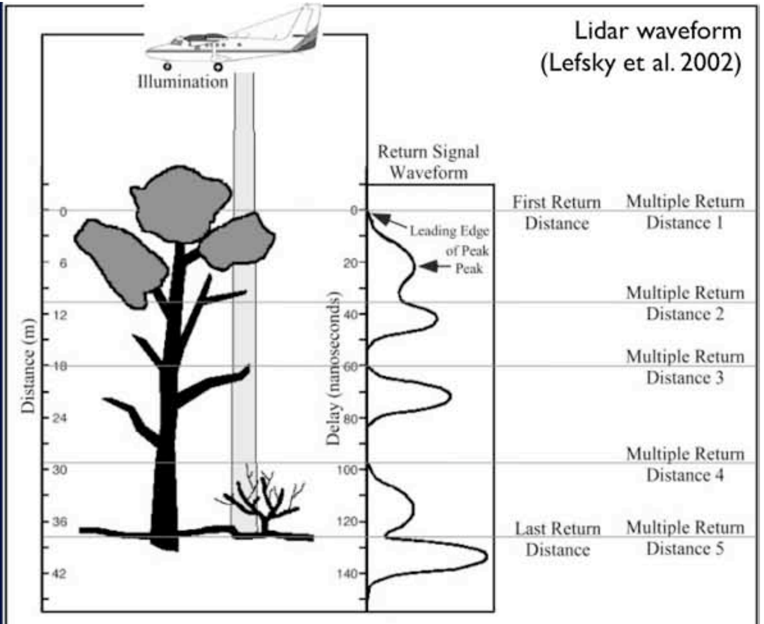
- Modified USDA Forest Service Forest Inventory and Analysis (FIA) design
- Systematic sample on 1.25 km grid (North Yuba)
- Random sample stratified by diameter class (Garcia-Mailliard)
- Aboveground live and dead trees, shrubs, coarse woody debris, litter
- Tree species, diameters at 1.37 m, heights of subsample, crowns of subsample
- Fire fuels, 1-, 10-, 1000-hour
- Species-specific allometric equations to calculate biomass



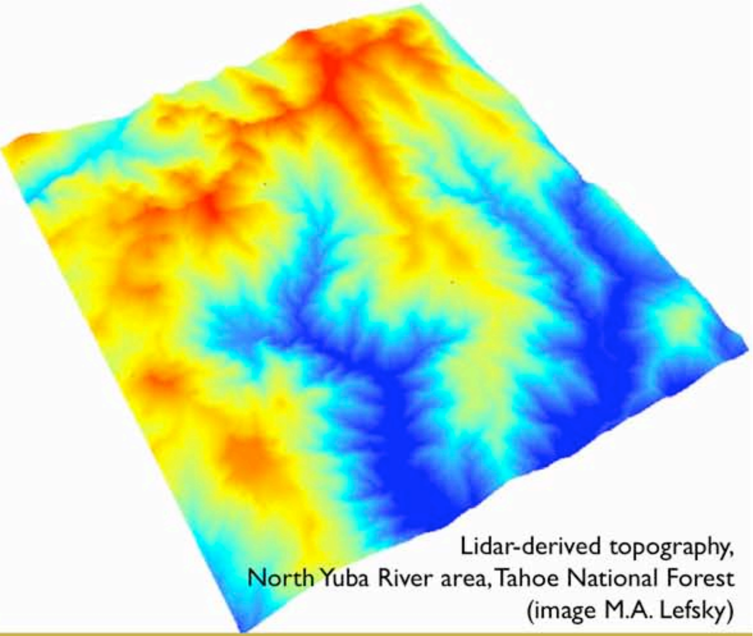
Crew leader Garrett Meigs (photo ©2005 P. Gonzalez)

Light Detection and Ranging (Lidar)

- Airplane altitude 800 m above ground
- Spatial density 1 shot m^{-2}
- Laser frequency 38 Hz
- Vertical accuracy (RMSE) ± 15 cm
- Horizontal accuracy (RMSE) ± 50 cm
- Swath width 580 m
- Employed progressive morphological filter to determine ground elevation at 2 m horizontal resolution
- Determination of canopy height from Lidar first return



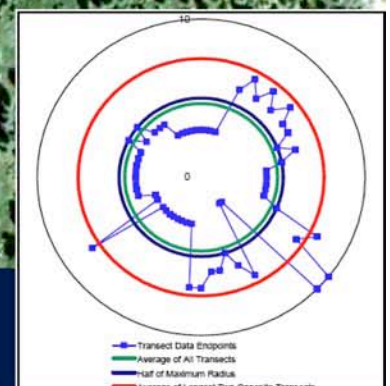
Lidar waveform (Lefsky et al. 2002)



Lidar-derived topography, North Yuba River area, Tahoe National Forest (image M.A. Lefsky)

QuickBird High-Resolution Satellite

- Orbital altitude 450 km
- Panchromatic resolution 60 cm
- Multi-spectral resolution 2.4 m
- Horizontal accuracy (RMSE) ± 6.2 m
- Delimitation of forest area from Normalized Difference Vegetation Index (NDVI)
- Crown detection from filtering of local maxima and minima
- Spatial data layers of crown perimeters and crown diameters



Top: QuickBird Satellite (DigitalGlobe, Inc.)
Bottom: QuickBird image, part of Tahoe National Forest, August 2, 2005
Right: Crown detection (G.P. Asner)

Calibration and Validation of Remote Sensing

QuickBird

Calibration: Regression analysis of field-measured biomass as a function of crown diameter

Validation: Compare crown diameters of 100 directly measured in the field and estimated from QuickBird data

Lidar

Calibration: Regression analysis of field-measured biomass as a function of Lidar height metrics

Validation: Compare Lorey's mean height calculated for 79 field plots and estimated from Lidar data

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

Lidar Biomass Regression Equations

North Yuba

$$B_{live\ trees} = 27.488705\ h_q - 46.41089\ h_{10} + 48.094323\ h_{20} - 45.54945\ h_{30} + 61.757518\ h_{40} - 36.13169\ h_{50} - 12.5304$$

(n = 39, r^2 = 0.80, $P(h_q)$ = 0.0001)

Garcia-Mailliard

$$B_{live\ trees} = 6.1660695\ h_q - 0.5045322\ h_{10}^2$$

(n = 40, r^2 = 0.86, $P(h_q)$ = 0.009)

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

Monte Carlo analyses of uncertainty of estimates of aboveground carbon in live trees

1. Field Measurements
    a. Diameter measurement error
    b. Allometric equation statistical uncertainty
    c. Sampling error of plot sample of entire area

2. Lidar
    a. Field measurement biomass uncertainty (from above)
    b. Regression equation statistical uncertainty

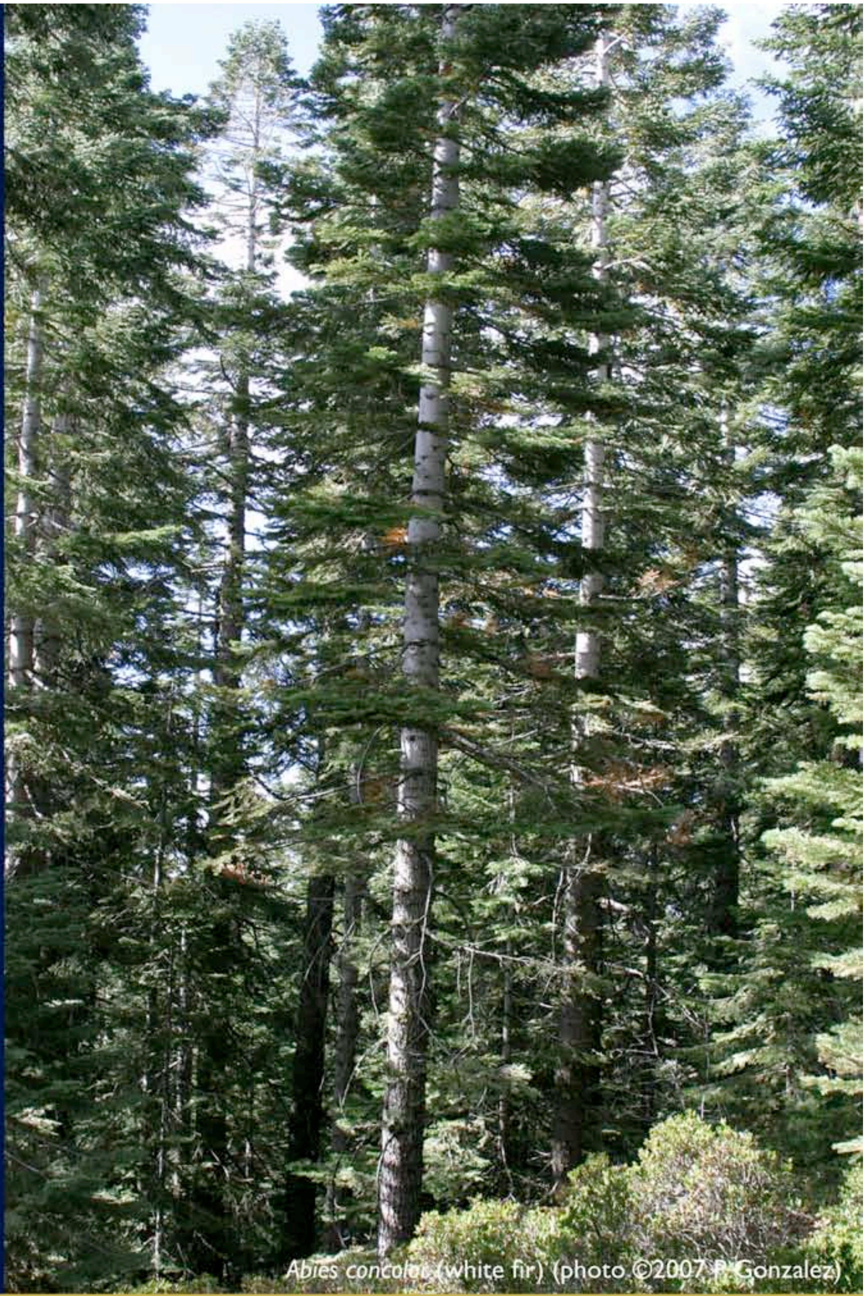
3. QuickBird
    a. Crown delineation sensitivity to NDVI and transects
    b. Crown delineation accuracy (from validation)
    c. Regression equation statistical uncertainty

Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Results

Forest Inventories North Yuba

- Measured and tagged 1523 trees of diameter >19.5 cm at h = 1.37 m
- Measured 1412 other trees of all diameters
- Eleven tree species
- Average density 330 ± 170 trees ha^{-1}
- Mean diameter 40 ± 21 cm



Abies concolor (white fir) (photo ©2007 P. Gonzalez)

North Yuba Forest Carbon Area Species Composition

		fraction	
		trees	biomass
Abies concolor	white fir	0.46	0.50
Abies magnifica	red fir	0.14	0.20
Acer macrophyllum	bigleaf maple	0.01	<0.01
Calocedrus decurrens	incense cedar	0.03	0.01
Pinus jeffreyi	jeffrey pine	<0.01	<0.01
Pinus lambertiana	sugar pine	0.09	0.09
Pinus monticola	western white pine	0.01	0.01
Pinus ponderosa	ponderosa pine	0.01	0.02
Pseudotsuga menziesii	Douglas-fir	0.10	0.13
Quercus chrysolepis	canyon live oak	0.06	0.01
Quercus kelloggii	California black oak	0.09	0.03

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

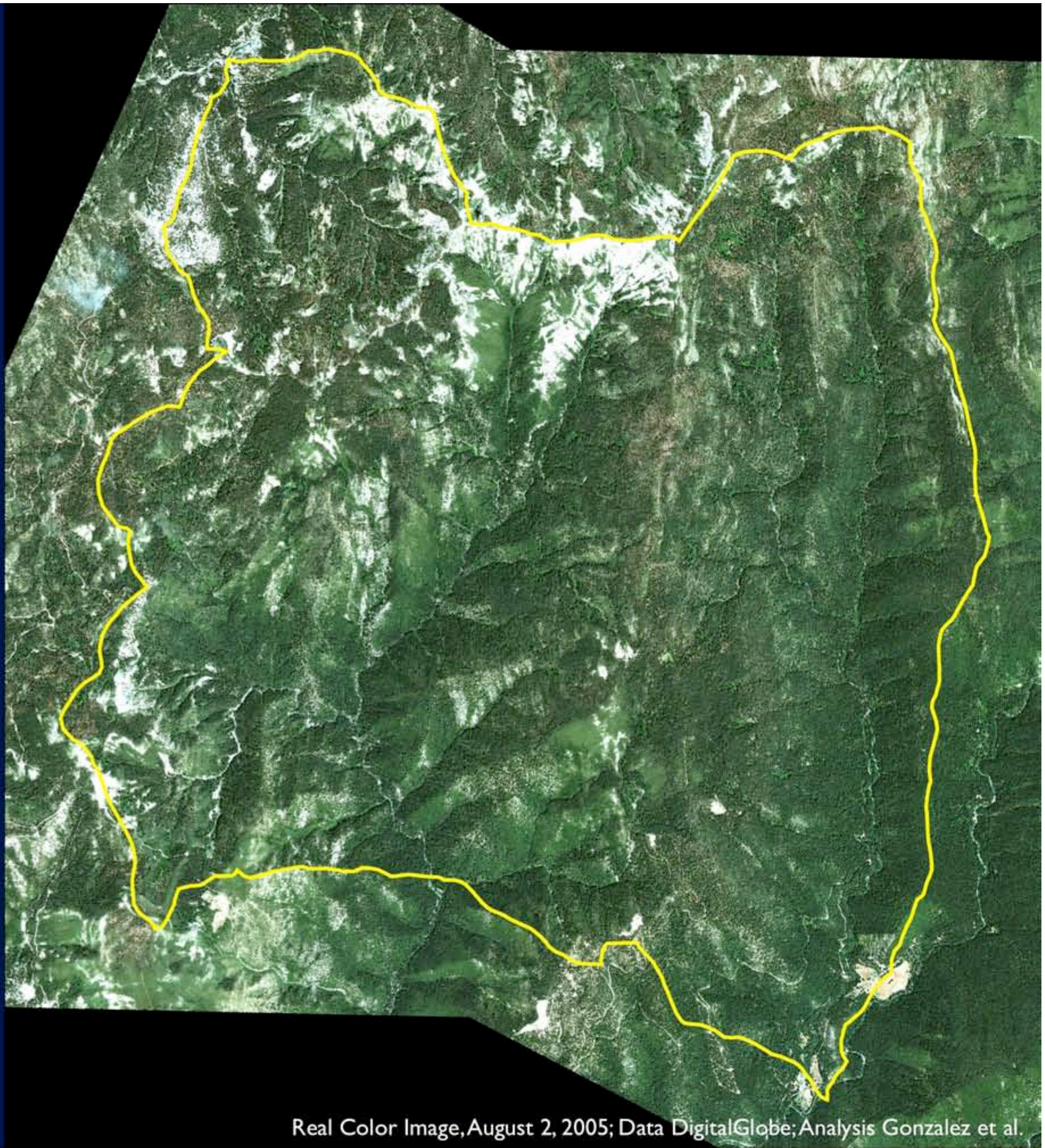
North Yuba Aboveground Forest Carbon

	Oak and Douglas-fir	Sierra mixed conifer	Red fir
plots	6	30	3
samples	24	108	12
Carbon (t ha^{-1}) (mean ± SE)			
live trees	210 ± 36	190 ± 3	360 ± 80
shrubs	0.5 ± 0.3	1.1 ± 0.2	0
dead trees	10 ± 6	19 ± 5	56 ± 16
coarse woody debris	1.3 ± 1.2	2.0 ± 0.6	8.5 ± 3.2
litter	37 ± 8	49 ± 5	81 ± 24
total aboveground	260 ± 51	260 ± 14	510 ± 120

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

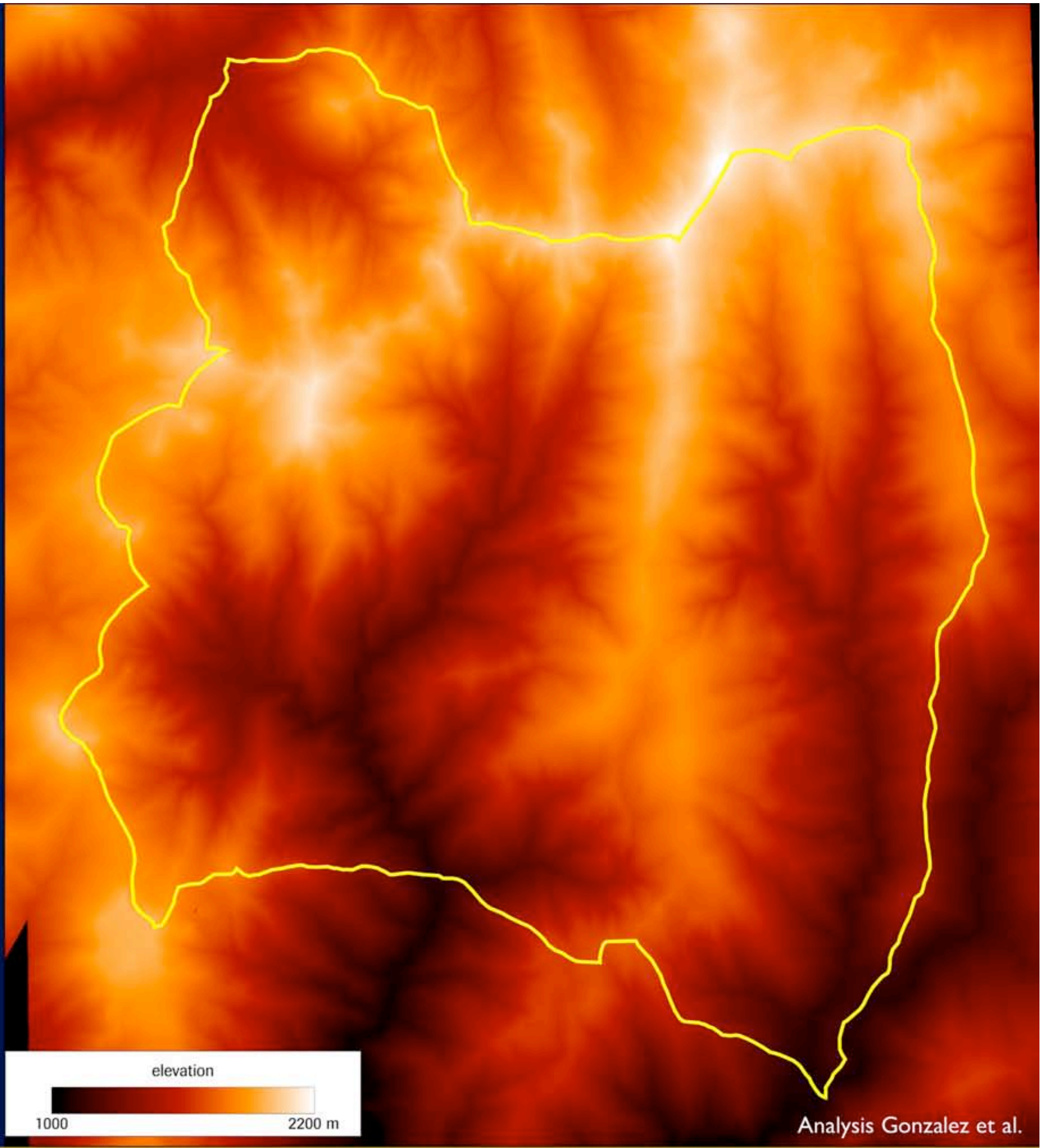
QuickBird North Yuba

- Detection and measurement of 681 000 tree crowns
- QuickBird crown diameters show significant accuracy (r = 0.82, P <0.05) when validated against field measurements
- QuickBird, however, undercounted trees by two-thirds due to shadows and topography



Lidar North Yuba

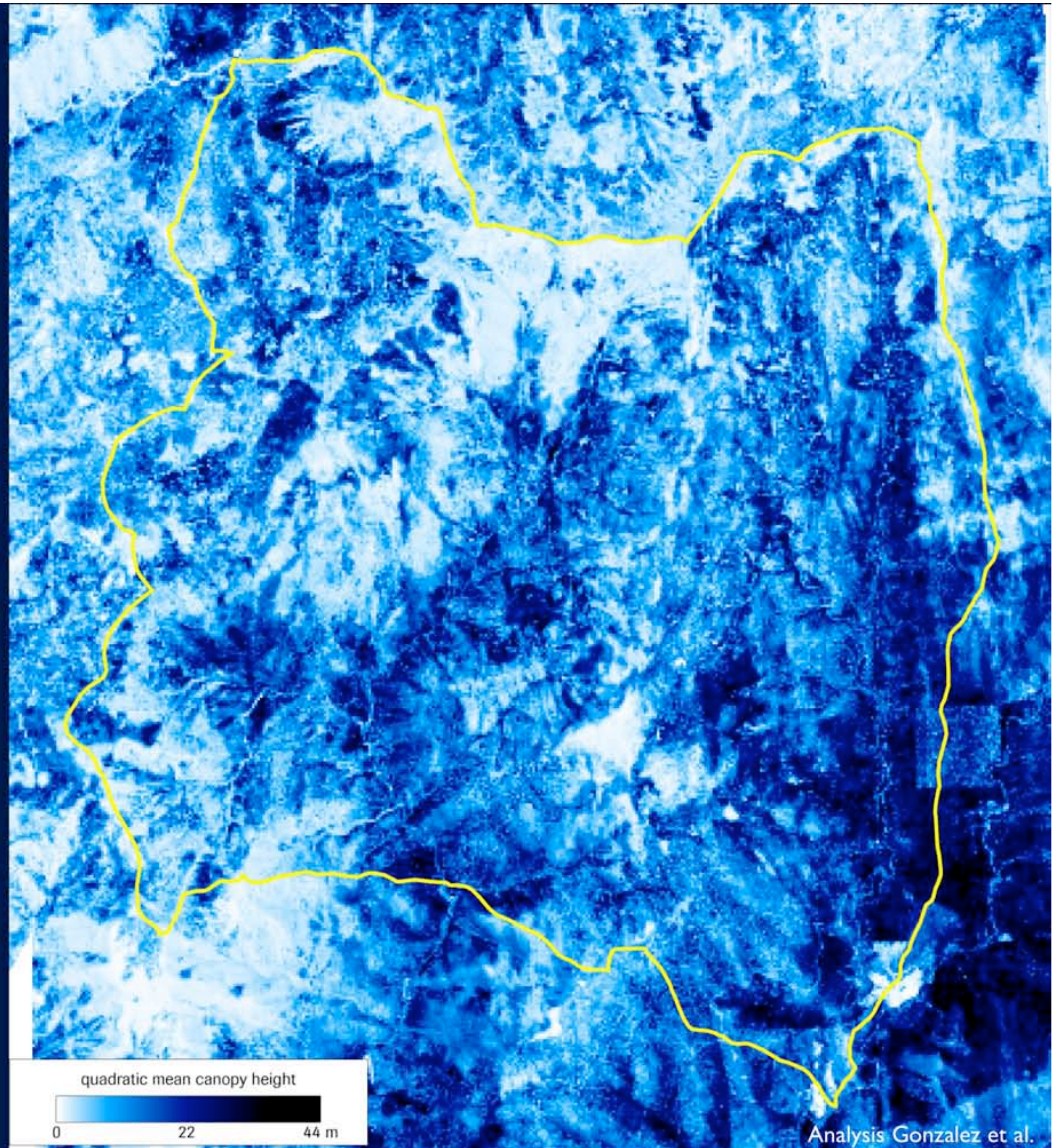
Elevation 1100-2200 m above sea level



Lidar North Yuba

Canopy height 34 ± 15 m
(mean maximum in 25 m pixels ± SD)

Lidar height showed significant accuracy (R = 0.89, P <0.0001) when compared to height calculated from field diameter



Lidar North Yuba

Aboveground Carbon in Live Trees

140 ± 0.8 t ha^{-1} (mean ± 95% Confidence Interval)

Forest Inventories
Garcia-Mailliard

- Measured and tagged 1100 trees of diameter >19.5 cm at h = 1.37 m
- Measured 2312 other trees of all diameters
- Eleven tree species
- Average density 330 ± 150 trees ha^{-1} (Garcia), 330 ± 160 trees ha^{-1} (Mailliard)
- Mean diameter 38 ± 15 cm (Garcia), 55 ± 31 cm (Mailliard)

Garcia-Mailliard Species Composition

		fraction			
		Garcia trees	Garcia biomass	Mailliard trees	Mailliard biomass
Acer glabrum	bigleaf maple			0.01	0
Arbutus menziesii	Pacific madrone	0.05	0.06	0.06	0.03
Lithocarpus densiflorus	tanoak	0.27	0.47	0.5	0.22
Pinus lambertiana	sugar pine	0.03	0.02		
Pseudotsuga menziesii	Douglas-fir	0.28	0.29	0.16	0.38
Quercus agrifolia	coast live oak	0.01	0.01		
Quercus chrysolepis	canyon live oak	0.03	0.02	0.01	0
Quercus kelloggii	California black oak	0.02	0.02		
Sequoia sempervirens	coast redwood	0.28	0.09	0.24	0.36
Torreya californica	California nutmeg	0.01	0	0.02	0
Umbellularia californica	California laurel	0.01	0.02	<0.01	<0.01

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

Garcia-Mailliard Aboveground Forest Carbon

	Garcia	Mailliard
plots	112	48
samples	28	12
Carbon (t ha^{-1}) (mean ± SE)		
live trees	100 ± 6.1	310 ± 32
shrubs	0.3 ± 0.1	0
dead trees	3 ± 3.3	8.3 ± 2.3
coarse woody debris	3 ± 0.7	2.6 ± 1.0
total aboveground	100 ± 7.5	320 ± 35

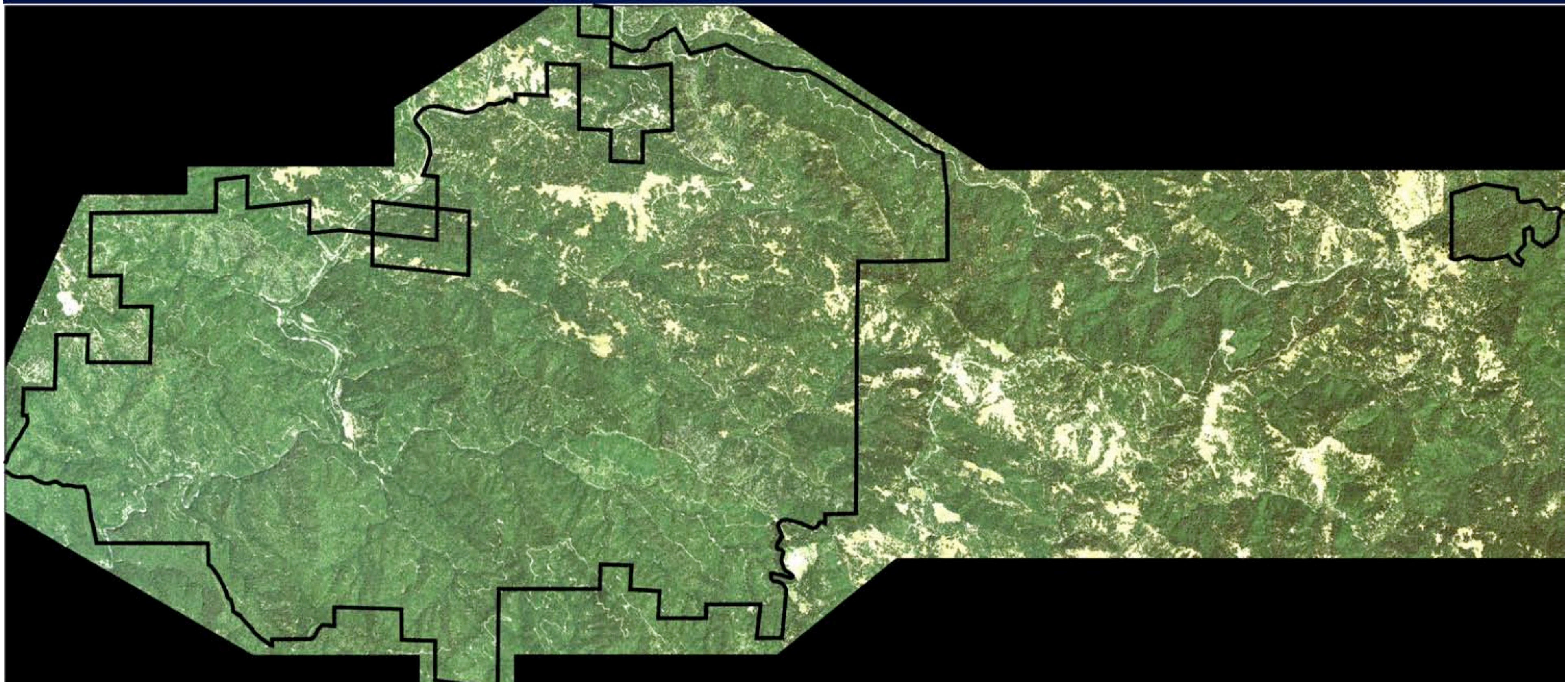
Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

QuickBird Garcia-Mailliard

Detection and measurement of 1.7 million tree crowns

QuickBird crown diameters show significant accuracy ($r = 0.82$, $P < 0.05$) when validated against field measurements

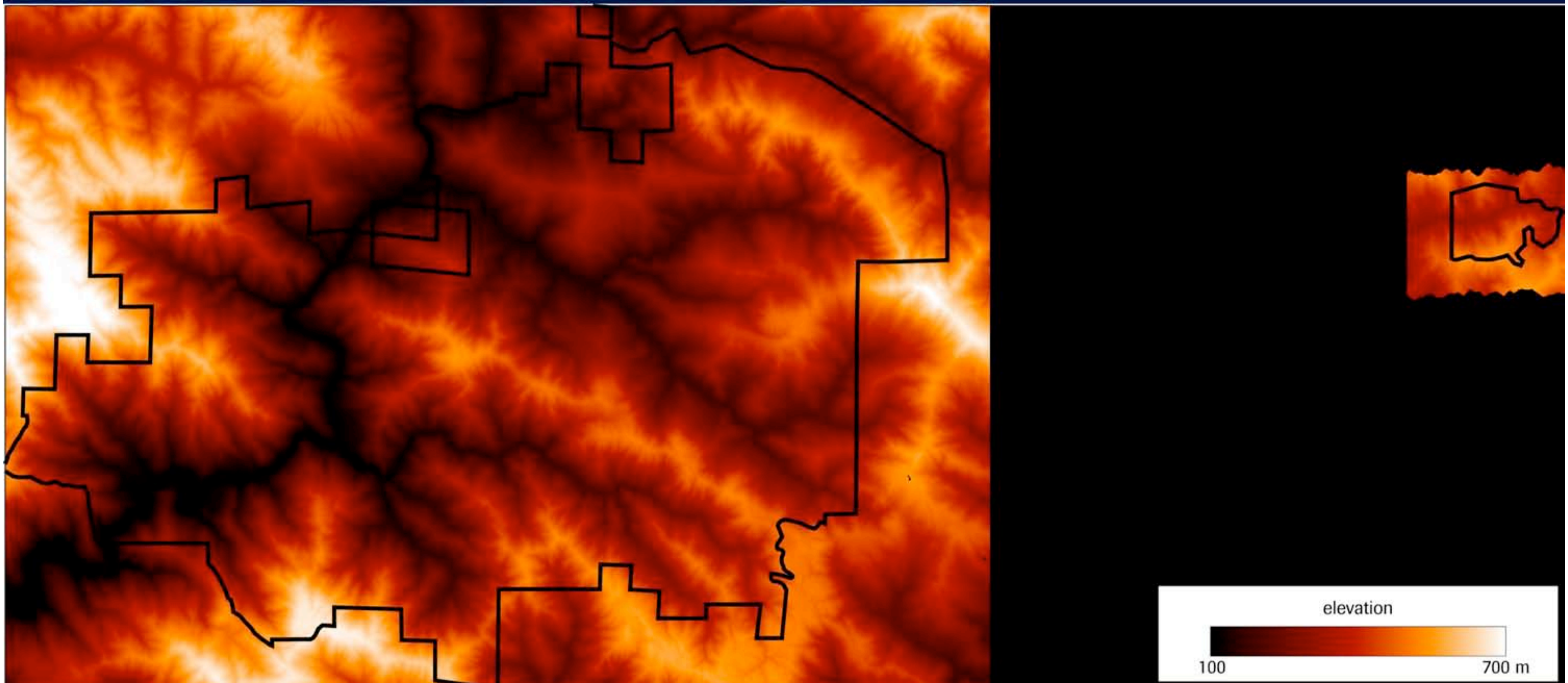
QuickBird, however, undercounted trees in Mailliard by two-thirds due to shadows



Real Color Image, August 5, 2005; Data DigitalGlobe; Analysis Gonzalez et al.

Lidar Garcia-Mailliard

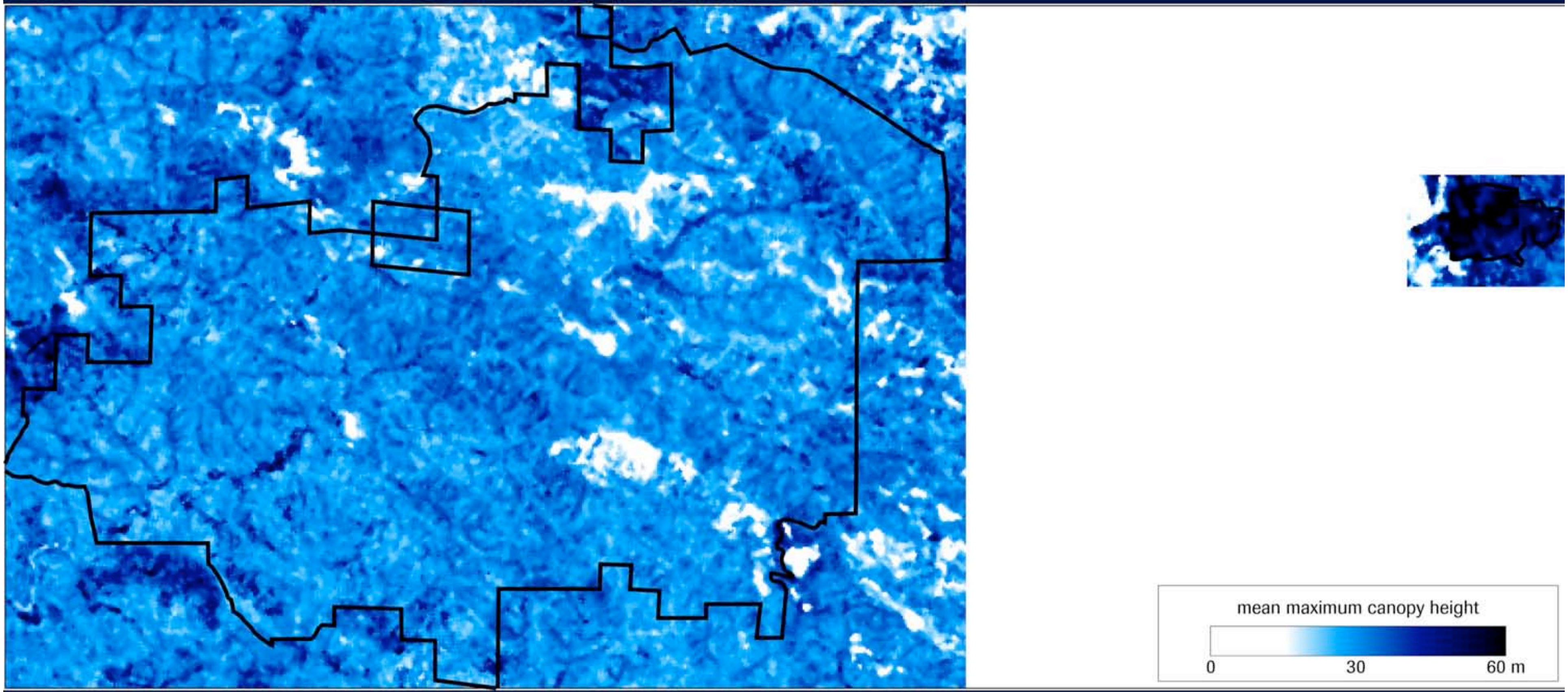
Elevation 100-700 m above sea level



Analysis Gonzalez et al.

Lidar Garcia-Mailliard

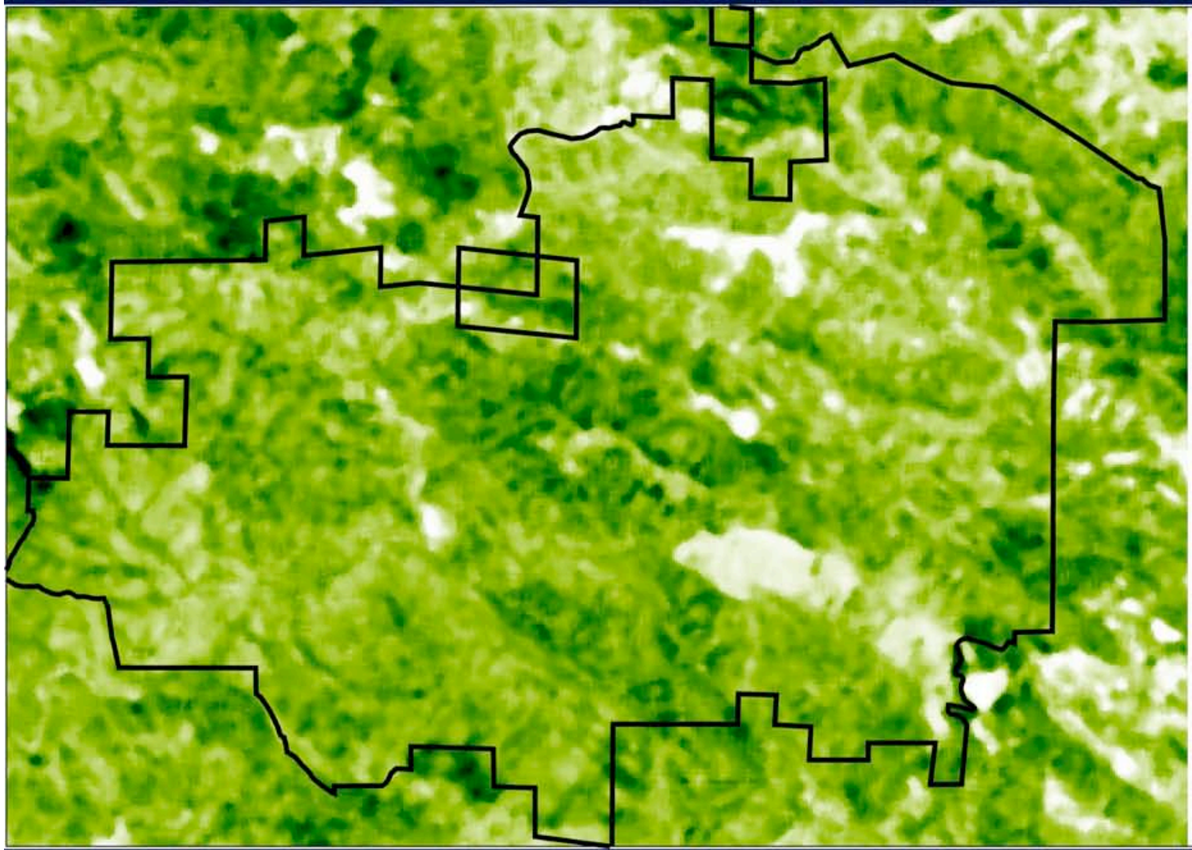
Canopy height 29 ± 6 m (Garcia), 53 ± 9 m (Mailliard) (mean maximum in 25 m pixels ± SD)
Lidar height showed significant accuracy (R = 0.94, P <0.0001) when compared to height calculated from field diameter



Analysis Gonzalez et al.

Lidar Garcia-Mailliard

Aboveground Carbon in Live Trees 82 ± 0.8 t ha^{-1} (mean ± 95% Confidence Interval)



aboveground live biomass

0 350 700 t ha^{-1}

Analysis Gonzalez et al.

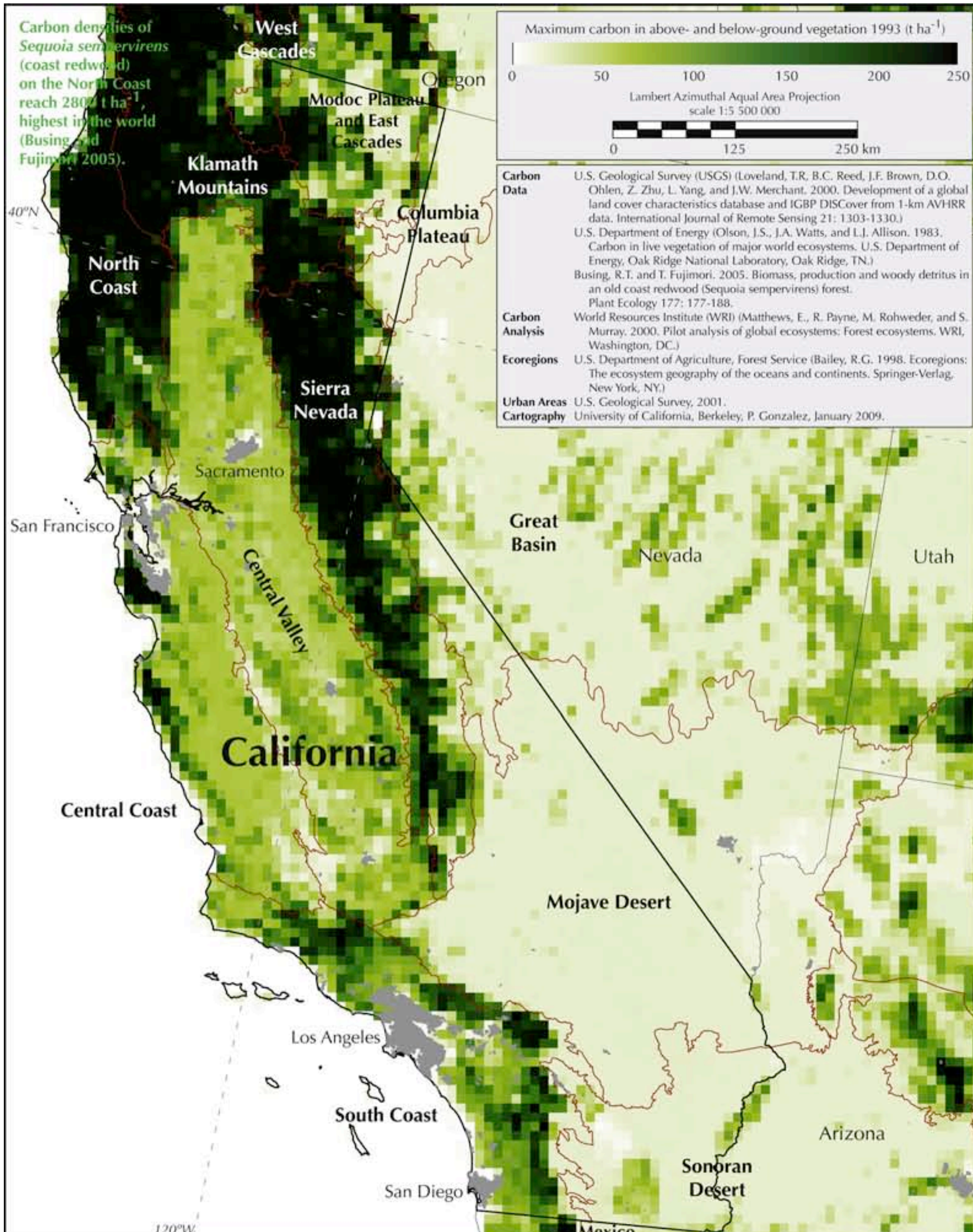
Aboveground Live Tree Carbon from Monte Carlo Analyses

Research area	Forest type	Field measurements Mean ($t\ ha^{-1}$)	Field measurements 95% CI ($t\ ha^{-1}$)	Field measurements Uncertainty (%)	Lidar Mean ($t\ ha^{-1}$)	Lidar 95% CI ($t\ ha^{-1}$)	Lidar Uncertainty (%)	QuickBird Mean ($t\ ha^{-1}$)	QuickBird 95% CI ($t\ ha^{-1}$)	QuickBird Uncertainty (%)
North Yuba	All	200	90	44	140	0.8	0.6	130	1.3	1
Garcia	Secondary coast redwood	97	27	73	80	0.7	0.8	120	3	3
Mailliard	Old-growth coast redwood	310	130	42	200	4	2	140	10	7
Garcia-Mailliard	Area-weighted average	100	24	24	82	0.6	0.8	120	3	3

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Conclusions



High Carbon Forests

Coast Redwoods, California

$1600\text{-}2800 \text{ t ha}^{-1}$

highest carbon density in the world (Busing and Fujimori 2005)

$200\text{-}310 \text{ t ha}^{-1}$

Mailliard Redwoods (Gonzalez et al., this research)

Sierra Nevada conifers, California

$140\text{-}200 \text{ t ha}^{-1}$

(Gonzalez et al., this research)

Amazon rainforest

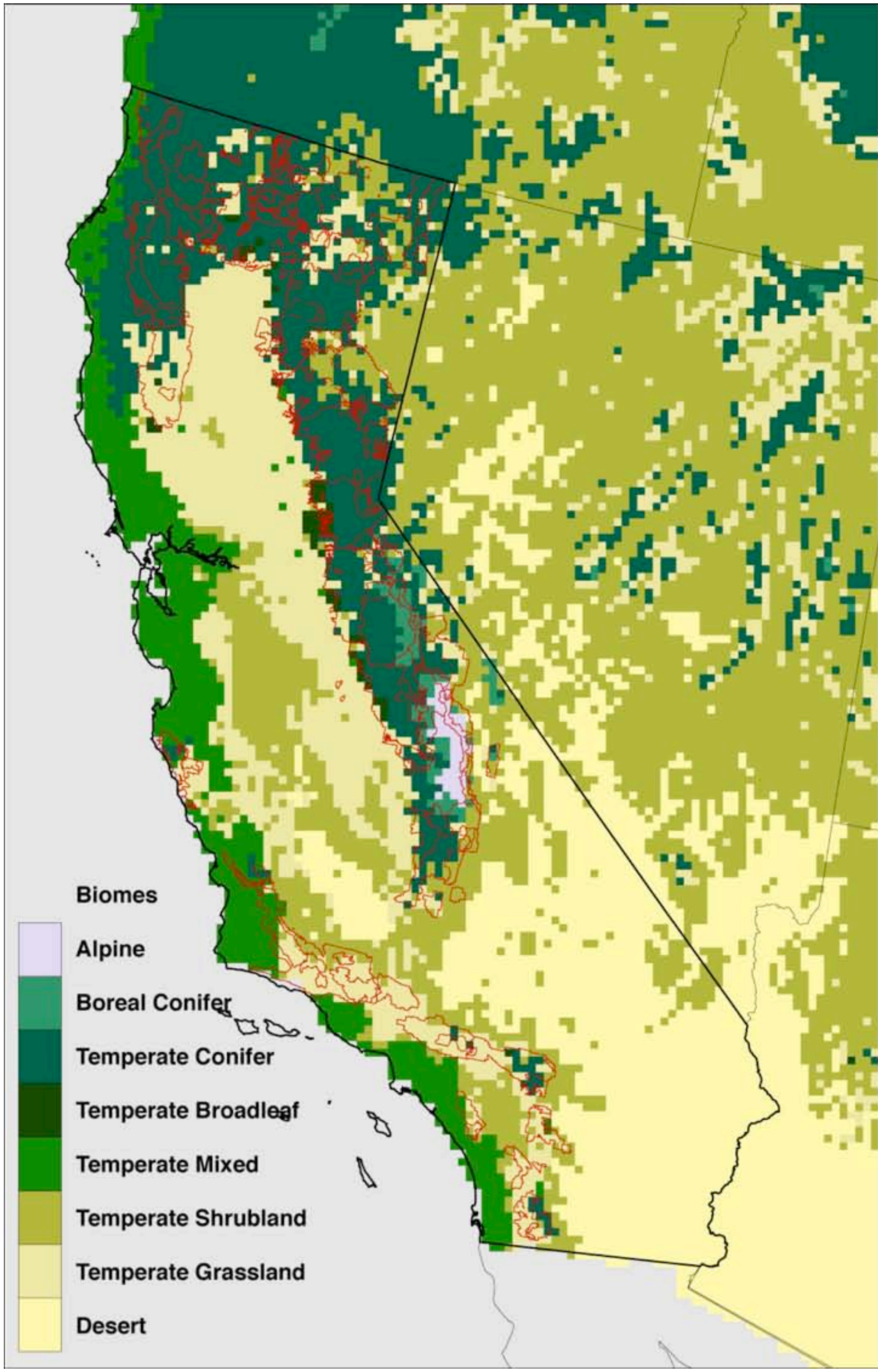
$170 \pm 9 \text{ t ha}^{-1}$

(Baker et al. 2004)

Practical Considerations

	Lidar	QuickBird
Uncertainty	<1% to 2%	1% to 7%
Logistics	airplane, sensor	purchase data
Data processing expertise	moderately common	unique capabilities
Cost	$$$$	$$

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.



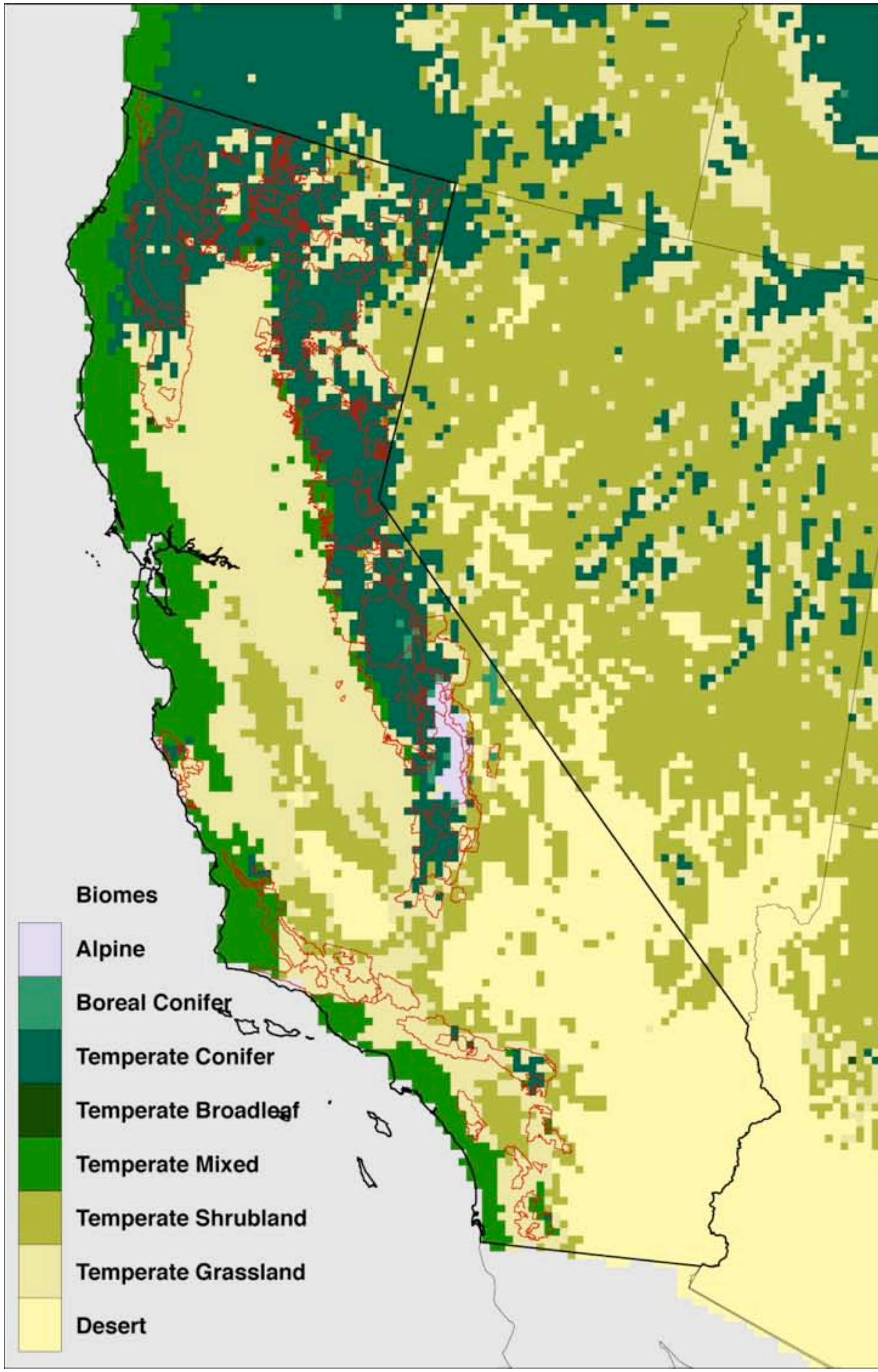
Potential Vegetation
1961-1990

MC1 Dynamic Global Vegetation Model
8 km Spatial Resolution

Manuscript in preparation:
P. Gonzalez, J.M. Lenihan, R.P. Neilson, R.J. Drapek

Climate Data:
Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25: 693-712.



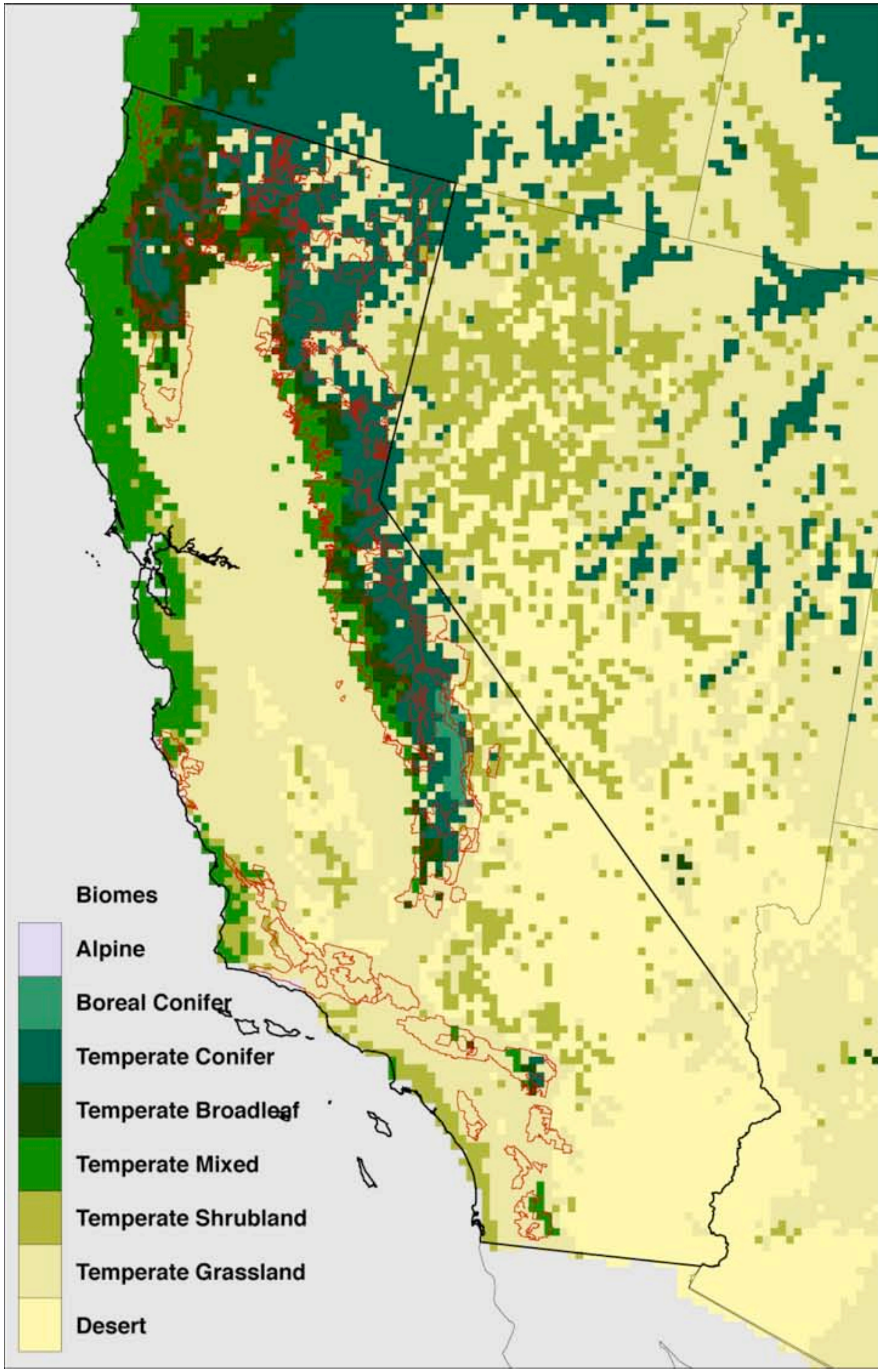
Potential Vegetation 2071-2100

Complete Agreement of Nine General Circulation Model-Emission Scenario Combinations MC1 Dynamic Global Vegetation Model

Manuscript in preparation:
P. Gonzalez, J.M. Lenihan, R.P. Neilson, R.J. Drapek

Climate Data:
Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25: 693-712.



Potential Vegetation 2071-2100

Any Change Among Nine General Circulation Model-Emission Scenario Combinations MC1 Dynamic Global Vegetation Model

Manuscript in preparation:
P. Gonzalez, J.M. Lenihan, R.P. Neilson, R.J. Drapek

Climate Data:
Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25: 693-712.

Remote Sensing and Field Measurement of Forest Carbon in High Biomass California Forests

Conclusions

1. Airborne Lidar provides forest carbon estimates with lower uncertainty and higher accuracy than QuickBird high-resolution satellite data.
2. Monte Carlo analyses of uncertainties from field measurements, remote sensing accuracy, and regression equations, can reduce the uncertainty of forest carbon density estimates to levels lower than published forest inventory carbon estimates.
3. Local field measurements of individual trees are essential to calibrate remote sensing variables to aboveground biomass and to validate remote sensing estimates of tree dimensions.
4. Sierra Nevada and coast redwood forests in California contain carbon at densities as high or higher than tropical rainforest.
5. A method that combines field measurements, Lidar, and Monte Carlo analysis can produce wall-to-wall spatial data layers and robust estimates of forest carbon for REDD projects.
6. A statewide forest carbon monitoring system could use high resolution, low uncertainty methods such as this for high biomass areas and less expensive methods for low biomass areas.

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, M. Palace. Manuscript in review.

View from Democrat Peak towards Sierra Buttes, Tahoe National Forest, California (photo ©2007 P. Gonzalez)